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Review Article

Resistance to Sliding in Orthodontics: A Systematic Review

Hamza Tageldin[1], Maria Cadenas de Llano-Pérula[2], Patrick Thevissen[3], Jean-Pierre Celis[4], Guy Willems[5*]

[1]PhD student, Department of Oral Health Sciences-Orthodontics, KU Leuven & Dentistry, University Hospital Leuven, Leuven, Belgium

[2]Staff member, Department of Oral Health Sciences-Orthodontics, KU Leuven & Dentistry, University Hospital Leuven, Leuven, Belgium

[3]Professor, Department of Oral Health Sciences-Forensic Dentistry, KU Leuven & Dentistry, University Hospital Leuven, Leuven, Belgium

[4]Professor, Department of Materials Engineering (MTM), Faculty of Engineering, University of KU Leuven, Leuven, Belgium

[5]Professor and head, Department of Oral Health Sciences-Orthodontics, KU Leuven & Dentistry, University Hospital Leuven, Leuven, Belgium

*Corresponding author: Professor Dr. Guy Willems, Department of Oral Health Science - Orthodontics, Katholieke Universiteit Leuven Kapucijnenvoer 7, B-3000 Leuven, Belgium, Tel: +32 16 33 24 59; Fax: +32 16 33 75 78; Email: guy.willems@med.kuleuven.be

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Abstract

Background and objectives: Resistance to sliding (RS) and friction in orthodontics are matters of interest and widely covered in literature. This systematic review aims to give an overview of studies evaluating the resistance to sliding in orthodontics in relation to the impact of related parameters such as material properties, ligation force, etc.

Search Method: An unlimited electronic search was performed in three data bases (PubMed, Web of Science and Grey Literature Report), including all studies published until the 26th of March 2015. In addition, a manual search was performed of all reference lists to detect any study that could have been missed by the electronic search.

Selection criteria: Studies that addressed a measurable correlation between friction or RS and other parameters were selected and reviewed.

Results: The electronic search resulted in a list of 1420 non-duplicate studies. In addition, 9 more were selected by manual search. Only 245 studies were considered eligible after applying the selection criteria.

Conclusion: Parameters involved in RS as well as their influence on both RS and orthodontic treatment were clearly identified. Some parameters are not sufficiently covered in literature and require further investigations.

Keywords: Friction; Resistance to Sliding; Orthodontics; Bracket; Archwire; Systematic Review; In Vitro

Introduction

The main concern of orthodontists has always been to achieve the most efficient, time-saving and successful treatment rendering optimal and satisfactory results for the patient. In order to achieve this target, it is important to fully understand the various factors and conditions involved in orthodontic tooth movement.

The friction generated between bracket and archwire plays an important role in this respect. From a mechanical point of view, friction is defined as “the resistance to motion during sliding or rolling that is experienced when one solid body moves tangentially over another with which it is in contact” [1].

In the last few decades, multiple orthodontic studies have reported on the role of friction in various clinical simulations. However, they actually reported resistance to sliding (RS), which is not interchangeable with the term "friction". RS is a more comprehensive concept than friction because it also includes other components that resist sliding such as binding and notching [2]. The term RS will be the only one used in this review except when static friction is expressed, which is the force required to initiate sliding or rolling. Many factors affect RS between bracket and archwire, such as the surface roughness of used materials [3] and bracket/archwire dimensions [4]. It is assumed that RS may have an impact on some aspects regarding orthodontic treatment such as the rate of tooth movement [5] or increase in anchorage requirements. Nevertheless, there is a lack of conclusive clinical trials [2].

In Orthodontics, force systems are designed to produce tooth movement in two fundamental ways relative to the archwire in fixed appliances [4,6]. Firstly, tooth movements can be achieved by using archwires with loops and levers, where there is no actual sliding between bracket and archwire. Secondly, movements can result from a translation of tooth and bracket over a continuous archwire. The latter involves actual sliding between bracket and archwire, which results in frictional forces resisting the motion in an opposite direction (RS).

This review was conducted based on the second type of tooth movements, considering in vitro studies that evaluate the bracket/archwire system as it is the most commonly used fixed system to correct malocclusion in orthodontic practice. It is well known that although there are many clinical studies related to RS, none of them have been able to measure RS *in vivo* so far. Although in-vitro findings cannot be extrapolated to in-vivo settings due to the possible interaction of different biological variables, such as periodontal ligaments and bone condition, a considerable amount of very valuable information has been reported about RS measurement using different in-vitro trials. Inability to fully replicate the biological considerations possibly influencing RS is an obvious disadvantage of the in-vitro trials. However, a review and analysis of in-vitro studies may provide information on material and mechanical aspects involved in RS. To this end, we here reviewed in-vitro studies measuring RS.

Objectives

The aim of this study was to systematically review in-vitro studies considering RS in orthodontics, to shed light on the role played by different mechanical and material-related aspects on RS.

Materials and Methods

Protocol

The protocol for this review followed a review structure developed prior to the literature search. Reporting follows the PRISMA guidelines (www.prisma-statement.org).

Information sources and search strategy

An electronic search was performed in three different data bases, MedLine Database (Entrez PubMed, www.ncbi.nim.nih.gov), Web of Science (Inspec Database, apps.webofknowledge.com), and Grey Literature Report of the New York Academy of Medicine (www.greylit.org) (Table 1). The search included all articles published until the 26th of March 2015. A search string of keywords was developed based on the terms "friction", "orthodontics" and "resistance", which are the most commonly used keywords in the studies of interest (Table 1).

Data Base	Keywords (search strategy)	Number of results	Number of selected paper before duplicates removal
Pubmed From inception until 26th of March 2015	(Orthodontic[all fields] OR ("orthodontics"[MeSH Terms] OR "orthodontics"[all fields])) AND (Friction[all fields] OR Frictional[all fields] OR Resistance[all fields])	1351	355
Web of Science (Inspec) From inception until 26th of March 2015	TS=(Orthodontic OR Orthodontics) AND TS=(Friction OR Frictional OR resistance)	115	72
Grey Literature Report From inception until 26th of March 2015	Friction AND/OR Orthodontics	----	---

Table 1. Electronic search string used in this review

Eligibility

Primary selection of studies was based on their title and abstract. Selected studies fulfilled the inclusion/exclusion criteria listed in Table 2.

Study Selection

The studies obtained with the established search string were screened and selected based on the title and the abstract. A single examiner performed the selection according to inclusion/exclusion criteria (Table 2). An additional manual search was performed using the reference lists of the included studies. Additionally selected studies fulfilled the inclusion/exclusion criteria listed in Table 2.

A final selection was performed after a full text reading of the included studies. The previously used criteria (Table 2) were re-examined in the full text. Studies which did not aim to state a direct and measurable relation between RS and other related parameters were additionally excluded.

Inclusion Criteria	Exclusion Criteria
•Title/abstract inclusion criteria: 1-English, full text papers. 2-Studies considering and/or quantifying friction in orthodontic tooth movement using bracket/archwire system under different conditions. 3-Studies evaluating aspects possibly affected by friction 4-Studies evaluating material and mechanical properties possibly affecting friction.	**•Title/abstract exclusion criteria:** 1-Editorial letters, opinions, comments and reviews. 2-Studies considering frictional properties not related to orthodontics. 3-Studies related to orthodontics but not related to frictional properties. 4-Studies considering other orthodontic treatment modalities. 5-Studies considering other forces not in the context of RS (e.g. Interdental or occlusal forces). 6-Studies considering biologic effects of materials used in orthodontics.
•Full-text inclusion criteria: Studies that aim to state a direct and measurable relationship between RS and other related parameters	**•Full-text exclusion criteria:** Studies that do not aim to state a direct and measurable relationship between RS and other related parameters

Table 2. List of inclusion and exclusion criteria

Risk of bias in individual studies

The selected studies were subjected to an established quality assessment protocol (Table 3) and given a score. The scoring was done as follows: Good = 1, Average = 0.5 and Poor = 0. The scores of the 12 questions are shown in Appendix I. Accordingly, studies were grouped into three categories:

• Score of 5.5 or less: Low-quality papers

• Score 6 – 7.5: Low to moderate-quality papers

• Score of 8 or more: Moderate to high-quality papers

Data collection process

Figure 1 show the data extracted from the included studies. A data extraction sheet was developed and piloted. To facilitate comparison, studies were grouped according to the different testing situations used in the literature (Figure 2). These testing situations represented different factors or aspects that could affect or could be affected by RS during orthodontic treatment. Then, studies were compared per group descriptively. The first author collected the data and reviewed the studies collected. The second and corresponding author performed additional reviewing and cross-checking of findings.

Results

Study selection and study characteristics

An overview of the electronic search and selection is shown in a flow diagram following the PRISMA guidelines (www.prisma-statement.org) (Figure 3). The initial search retrieved 1466 records from all data bases (1351 PubMed, 115 Inspec, 0 Grey Literature Report). Once duplicates were removed, 1420 records were screened. Additionally, 9 records were added after manual search. After applying the selection criteria based

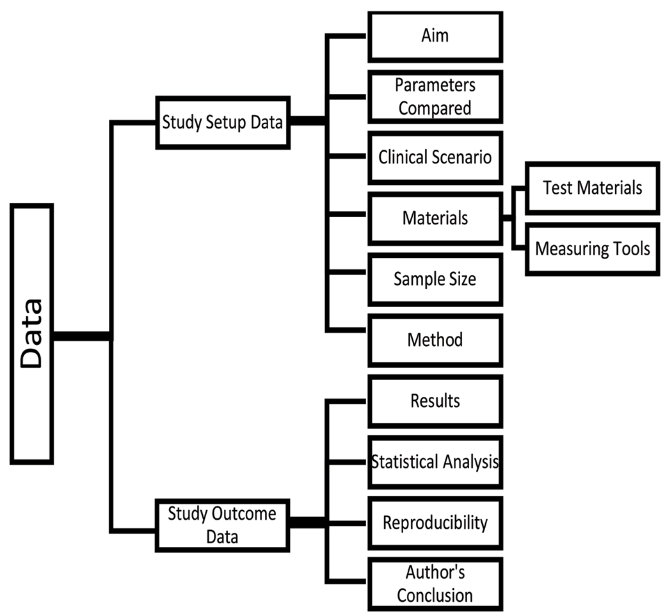

Figure 1. Set of data extraction.

on title and abstract (Table 2), 1039 records were excluded. Of the 390 full-text articles, 145 were excluded for not matching the purpose of the review. A total of 245 eligible studies were included in the present review.

Risk of bias of studies

The details of the quality assessment protocol are listed in Appendix I. Of the included studies, 17.55% were considered of a moderate to high quality, 25.71% were of low quality and 56.73% were of medium quality.

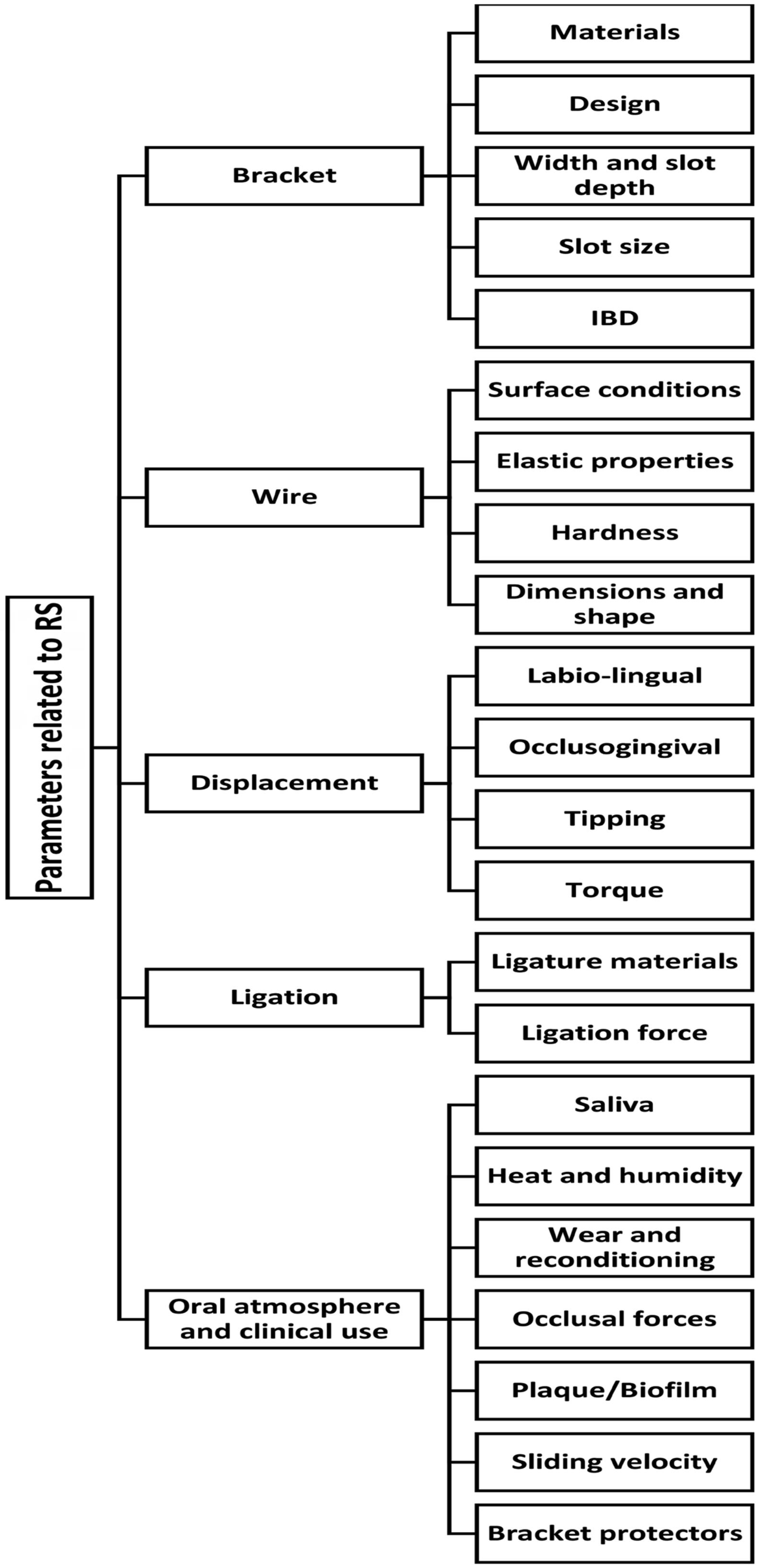

Figure 2. Classification protocol of included studies according to parameters related to the RS.

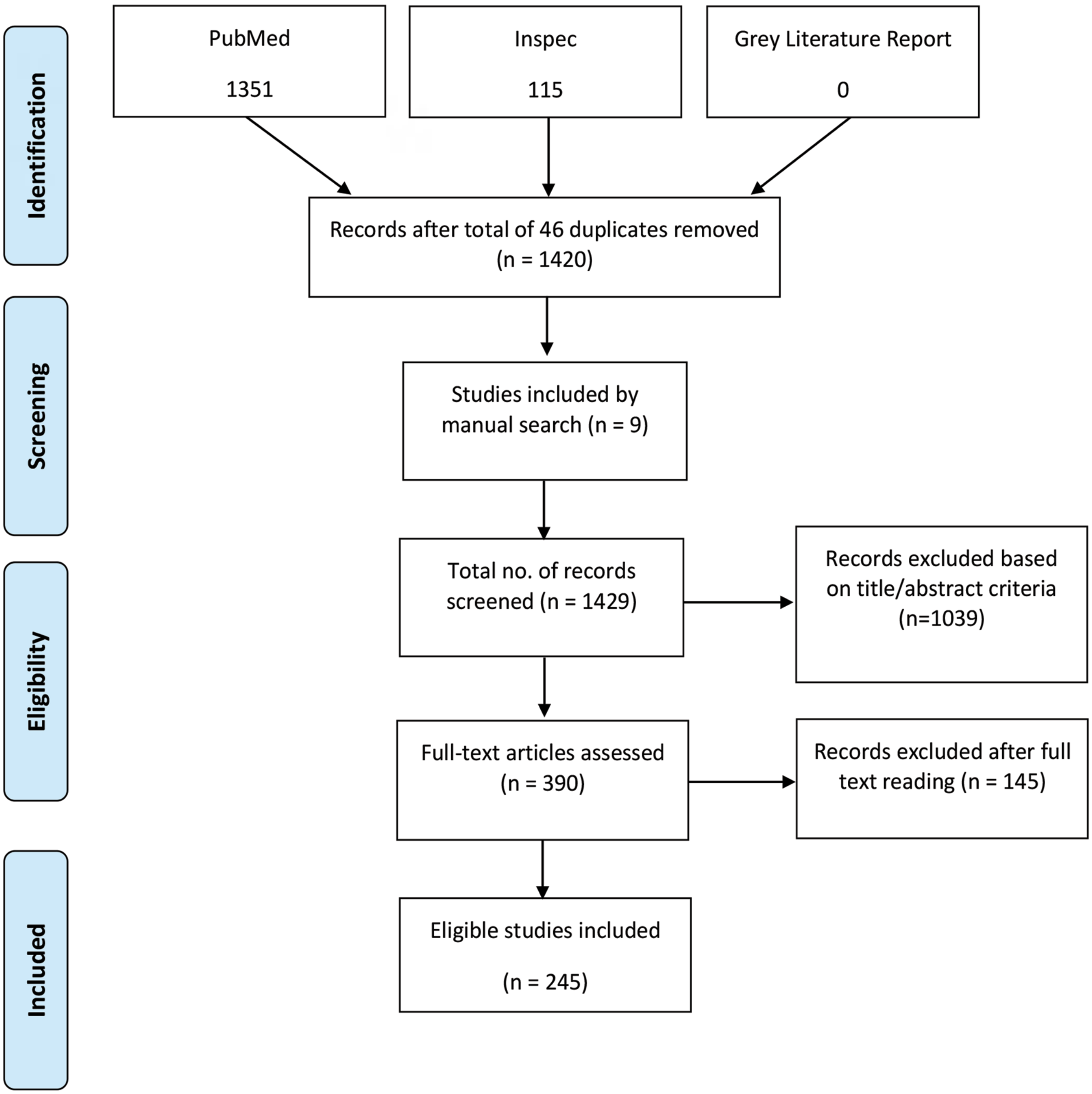

Figure 3. Illustrative PRISMA flow diagram revealing the general screening overview.

	Study title: Journal: Year:	1st Author: Vol.:	Page:
1.	Did the study obtain a clearly stated aim (objective)?		
	☐ Good	☐ Average	☐ Poor
2.	Were the selection criteria of test materials described?		
	☐ Good	☐ Average	☐ Poor
3.	Did the test materials show similar baseline characteristics?		
	☐ Good	☐ Average	☐ Poor
4.	Was the sample size of test materials reported?		
	☐ Good	☐ Average	☐ Poor
5.	Was the sample size of test materials ≥ 5?		
	☐ Good	☐ Average	☐ Poor
6.	Did the study obtain an adequate co-intervention?		
	☐ Good	☐ Average	☐ Poor
7.	Were the samples blinded?		
	☐ Good	☐ Average	☐ Poor
8.	Was the test frequency ≥ 3 for each test group?		
	☐ Good	☐ Average	☐ Poor
9.	Were the measurements subjected to intra-observer reproducibility tests?		
	☐ Good	☐ Average	☐ Poor
10.	Were the measurements subjected to inter-observer reproducibility tests?		
	☐ Good	☐ Average	☐ Poor
11.	Was the conflict of interests avoided?		
	☐ Good	☐ Average	☐ Poor
12.	Were the results statistically analyzed with an appropriate test?		
	☐ Good	☐ Average	☐ Poor
Score:			
Comments:			

Table 3. Quality assessment protocol.

Selected studies

The selected studies were found to relate many parameters to RS. All the selected studies investigated RS of different bracket/archwire combinations in vitro. Related parameters varied in their impact on RS. A more comprehensive overview is reported in the discussion section.

Discussion

Quality assessment protocol

In this review, a custom-made scale was used to assess the quality of the studies included (Appendix I). The studies were numerous and very diverse in designs and protocols, and it was impossible to use one of the reported quality assessment scales for this purpose. In addition, existing scales are not validated for the type of material researches in the present review. In this section, papers of higher quality and more related information were mainly discussed.

The relation between RS and related material and mechanical parameters is summarized as follows:

1. Bracket:

It is common in the literature to evaluate the properties of different bracket materials, dimensions or designs in relation to RS.

1.1. Bracket materials:

Brackets of different materials have different frictional properties due to differences in their chemical and morphological structure. It was widely reported that among different materials used for bracket fabrication, stainless steel (SS) brackets showed the least resistance to sliding due to smooth polished surfaces facilitating sliding [7-13]. On the other hand, aesthetic all-ceramic brackets were shown to have higher RS due to their porous, rough surfaces [8-10,12,14-18]. Even within the same bracket material itself, RS differed according to manufacturing technique. It was reported that sintered SS brackets were associated with less RS than cast ones, again due to smoother surfaces [19]. This may be an explanation of a proportional relation between RS and surface roughness of brackets. In terms of surface roughness of aesthetic brackets, glass-fiber reinforced brackets were reported to have less RS than ceramic reinforced ones [18]. Similarly, the monocrystalline sapphire (MCS) and single crystalline alumina (SCA) brackets were reported to have less -or at least comparable- RS than the polycrystalline alumina brackets (PCA) due to smoother surfaces of MCS [8,11,14]. On the other hand, it was reported that monocrystalline ceramic brackets were associated with higher RS than polycrystalline ceramic brackets in a dry setting, although they have smoother surfaces [20-22]. Different findings suggested that surface roughness of bracket materials may well not be the only important aspect playing a role in the RS. Findings differed when other parameters prevailed related to RS such as angulation [14,22], wire surface conditions [23] or ligation force [24]. Similarly, titanium brackets showed less RS than stainless steel ones although they had a rougher surface. Differences in findings were reported to be due to differences in manufacturing process resulting in differences in surface chemistry [25]. Additionally, the presence of an oxide film on the metal slot of composite brackets played a role in decreasing their static friction to levels comparable to stainless steel brackets as it acts as a barrier between the bracket slot and the metallic wire [20,26]. Furthermore, the sharp asperities of composite brackets led to less contact area between the bracket and the wire, lowering the force required to initiate sliding [20].

In addition, bracket materials of different hardness showed different RS. The harder SS brackets showed less RS compared to the softer titanium ones, which showed higher abrasion sensitivity [27]. On comparing three different models of SS brackets [SR-50 A, MiniDiamond® and Archist®], the SR-50A in the as-received state showed the lowest hardness values and the highest RS [28].

1.2. Bracket design:

A new trend in designing brackets is the insertion of dissimilar materials into brackets, e.g., slots and caps of self-ligating brackets (SLBs) [9,29]. The aesthetic ceramic brackets are highly demanded for their superior esthetic properties. However, their rough surface and decreased hardness compared to the conventional SS brackets has led to the introduction of metal or silica slots into conventional designs. It was found that the introduction of metal or silica slots led to a marked reduction in RS due to their smoother surfaces than those of the all-ceramic brackets. Similar findings were reported when the metal insert is wide enough to prevent contact between test wire and slot walls. This was supported by consistent agreement in the literature [9,11,12,14-17,20,26,30].

When the caps of SLBs were made of dissimilar materials than the bracket material itself, RS behaved differently. SPEED® SLB showed higher RS than other SS SLBs [29] because of its NiTi clip due to differences in coefficient of friction (COF) between NiTi and SS, which led to higher RS of SPEED® when there was no clearance between wire and bracket [29]. Shape and mechanism of the cap of SLBs played a role in terms of RS. SLBs with a bell-shaped cap as Time 3® were reported to have higher RS than other SLBs with a little cap due to higher ligation force [31]. SmartClip® SLB showed higher RS than other types of passive SLBs as it has two clips causing binding of the wire [32]. However, those differences could be eliminated when round wires were used instead of rectangular large ones [31]. When SLBs with sliding caps (e.g. Damon®) were ligated to rectangular large wires, they created more contact with the wire leading to higher RS than other SLBs with caps sliding along a rail (e.g. Vision®) [31]. In the first order of angulation, it was found that the passive SLBs showed a higher static friction than active SLBs. This was due to the non-flexible slides of passive SLBs, which did not extend against the wire pressure as did the flexible springs of the active SLBs (acted as stress absorbent)[33].

Among the conventional ligated brackets, the design of the Tip-Edge® brackets resulted in less RS than the Mini-Diamond® brackets as the Tip-Edge® design allowed more wire clearance in the slot[34]. This was consistent with research on Tip-Edge® and Transmission Straight Archwire® brackets [35], which showed that high critical contact angles (θ_c)[a] due to the edge-off structure led to less influence of the binding component (BI) on RS by expanding the passive configuration.[b] Another example is the Synergy® brackets, which have a unique design allowing different manners of ligation. It was reported that ligating the inner wings of the Synergy® brackets leads to marked reduction in RS[36].*

Addition of bumps and rounded slot walls did not affect RS below a critical contact angle (θ_c) during tipping since RS is independent of contact area. However, rounded slot walls increased θ_c leading to less impact of BI on RS but at the expense of some control of root positions [37-40]. Rounded slots create more clearance between wire and bracket and allow offsetting the significant contribution of elastomeric ligatures to overall friction in the system [40]. On the other hand, addition of bumps led to a higher BI component than conventional brackets due to bending of the wire in the slot before negotiating the slot walls [37].

Slot inclination may promote sliding depending upon the wire shape. Brackets with small deviation in the slot generated more contact with the rectangular archwires, leading to higher static friction [20]. On the other hand, when those brackets were coupled to round archwires, they caused wires to slide easier, leading to less static friction [20].

1.3. Bracket width and slot depth:

Bracket designs of different dimensions also have an impact on RS. Wider brackets are associated with smaller inter-bracket distances (IBDs) during the levelling stage of treatment, making the wire stiffer and hence decreasing θc, which leads to a higher BI component [33,41]. During labiolingual displacement, deeper slots allow more clearance between wire and bracket, and hence less RS [33]. On the other hand, no correlation was reported between RS and slot depth or bracket width during horizontal displacement [41].

[a]The angle up to which clearance exists between the wire and the bracket.

[b]The area below the critical contact angle (θ_c).

Differences in findings may have been due to differences in the study design.

It was reported that the narrower brackets were associated with less RS as they offered more clearance for the wire during tipping [42]. A proportional relation between RS and bracket width can be concluded [43,44]. However, inconsistent findings were reported because the ligation forces prevailed over other parameters related to RS[29]. Some studies reported that wider brackets caused less RS than narrower ones by allowing less angulation change of the archwire [6,45,46].

1.4. Bracket slot size:

Some studies evaluated RS among brackets of different slot sizes and there is a consistent agreement that the slot size does not affect RS per se. It is generally believed that slot size depends more upon the bracket/wire combination [19,45,47-50]. It is reported that the slot-filling bracket/archwire combinations produced the highest RS due to lack of clearance between wire and bracket [50]. Wires placed in the slot using the central positioning (CP) method and compared with those visually positioned, were found to offer more clearance than the wires that were visually placed [50]. These findings confirm that RS is mainly bracket/wire combination dependent, and that the slot size is not a determining variable per se.

1.5. Inter-bracket distance:

Another variant related to brackets that influences RS is the inter-bracket distance (IBD[c]). If the degree of malocclusion increases, the IBDs decrease and the angulation between archwire and brackets increases, leading to stiffer wire and higher RS [31,47]. Hence, there is an inverse relation between IBD and RS consistent with some studies [43,51]. However, only one study reported that a change in IBDs to the extent generally encountered in canine retraction did not influence the force required to initiate sliding [44].

2. Wire:

2.1. Wire material (surface conditions):

Differences in archwire surface conditions were shown to have an impact on RS depending on the material used. Several studies reported that SS wire showed the lowest RS followed by NiTi and βTi due to differences in their surface roughness [10,11,15,19,25,42,52-54]. Others also reported that βTi wires showed higher RS than SS ones, but comparable to or lower than NiTi ones [9,23]. Differences in findings could be due to differences in medium and setup of testing. Additionally, βTi wires showed highest RS among NiTi and SS wires due to adherence to the slot surface, but SS wires showed slightly

[a] The distance between two centers of adjacent brackets

higher RS than NiTi wires suggesting that it could be due to differences in wires stiffness [17,55]. In addition, cobalt chromium (CoCr) and SS wires were reported to show less RS than NiTi and βTi wires due to differences in surface roughness [10].

Coating and ion implantation of wires for aesthetic reasons also had an impact on RS. It was reported that surface refinement by ion implantation or coatings of wires resulted in less RS than uncoated, untreated wires [40,56-58]. The newly introduced TMA™ wires such as Honeydew and ion-implanted TMA™ wires, showed lower RS than conventional TMA™ wires although still higher than SS wires [59]. Some studies also reported that TMA™ wires showed higher RS than SS wires [14,40,60,61]. TMA™ wires were reported to have high RS because of their titanium-rich layer, which breaks down, reacts, adheres, and breaks away resulting in stick-slip phenomena [61].

Coated wires were also reported to increase RS [20,62,63]. This is due to stripping or scratching of the coating during sliding [20,63] or due to adhesion that arises from molecular forces between the coating and the bracket surfaces [20].

2.2. Wire material (elastic properties):

Differences in mechanical or elastic properties of archwires have an impact on RS. A slight increase in RS with stiff archwires was reported during sliding with a cycle of relative tipping and up righting between bracket and archwire [6]. This is consistent with some studies reporting that stiffer wires were associated with higher RS values if there was tipping between brackets and wires [8,9,64,65]. A clinical benefit of using flexible wires is that during alignment stage, misaligned or maloccluded teeth can easily negotiate greater angulations, resulting in lower RS values [66].

2.3. Wire hardness:

Hardness of wires differs and affects RS behavior of wires. A decrease in hardness values of wires is generally associated with an increase in abrasive wear. Accumulation of wear debris in turn leads to an increase of RS values [67-72].

2.4. Wire dimensions and shape:

It is widely accepted that wires of larger sizes are associated with higher RS rather than smaller ones as clearance between bracket and wire decreases [6, 8,10,11,16,17,19,23,29,34,42,43,50,52,53,55,57,60,64,66,73-77]. RS depends mainly on the vertical dimension of the wire [6]. As long as the vertical dimensions of the wires are smaller than the bracket slot size, and in the absence of angulation, the RS value is independent of the wire size [50,78]. However, smaller wires may still act unpredictly depending on the wire itself. Smaller βTi wires showed higher RS than larger ones due to tilting of wires under ligation force, resulting in a prominent edge and increased wear [27].

Considering different wire cross-section shapes, when clearance no longer exists between bracket and wire, rectangular wires showed higher RS than round wires did [19,27,29,79-81].

On the other hand, some authors reported that a difference in wire cross-section shapes had no influence on static friction [27,82]. In the absence of angulation or tipping, rectangular wires showed less clearance in the slot buccolingually than round wires, resulting in a higher ligation force with rectangular wires and, hence, higher RS value [11,40,83,84]. One study reported that a round wire of size 0.016-inch showed a virtually similar RS value of a rectangular wire of size 0.016×0.022-inch of the same material [6]. Thus, for mesiodistal tooth movement, rectangular wires are preferred because of their additional feature of buccolingual root control.

3. Displacement in 3D: Translation and rotation:

3.1. Labio-lingual displacement:

Generally, an increase in labiolingual displacement results in a reduction of clearance between bracket and archwire, leading to a higher RS value. Static friction rises with an increase in labiolingual displacement especially when θc is exceeded [33,36,74,85]. Similarly, RS increases with augmented displacement. In other words, the bending moment produced by a wire and the resulting shear force during sliding predictably increase as the deflection increases above a certain critical angle θc. This varies depending on the bracket/wire combination used [74,86,87]. Only one study compared static friction between wire ligated on a convex arch and another ligated on a flat plate [88]. The brackets set on a convex arch had a different buccolingual relation than those set on a flat plate without angulations. Furthermore, the wire ligated to a convex arch model showed a higher static friction than that ligated on a flat model because the angulation of the wire to the bracket increased the contact areas on friction components.

3.2. Occlusogingival displacement:

Some experimental set-ups evaluated RS under occlusogingival displacement, i.e. during the leveling stage of clinical treatment. Similar to other types of displacement, an increase in occlusogingival displacement led to a decreased clearance between bracket and wire, leading to a higher RS [16,33,65,74,89,90]. In such types of malocclusion, the common practice is to use more flexible archwires as they show a smaller BI component than stiff wires, as indicated above. RS was reported to increase with occlusogingival displacement[65] but interestingly, both tested wires (L&H

Titan® and Sentalloy®; super elastic NiTi) showed lower RS value at a 4 mm displacement than at a 3 mm one [65]. It was suggested that the formation of stress-induced martensite resulted in lower stiffness and thus reduced BI component.

3.3. Tipping:

Several studies evaluated RS during second-order angulation or tipping. Many authors reported that RS markedly rises with increasing tipping as clearance between wire and bracket no longer exists (above θc) and a larger contact area and friction component are created [7,8,14,22,34,35,63,64,66,75,81,91-101]. The friction force (FR) seems to equal RS in the passive configuration below θc, [91] while whenever clearance disappears and angulation exceeds θc, the BI component (moment) is additionally involved in RS [91]. The BI moment depends on the mechanical properties or stiffness of the archwire as explained above. Wider periodontal ligament spaces cause the bracket tipping to increase, leading to higher RS value [94].

Some study designs simulated the biological retarding forces which face the root by the surrounding tissues during sliding. This retarding resistance acts in an opposite direction to the traction force, causing the tooth to rotate or to tip around its buccolingual axis [6]. Virtually, that results in bracket tipping. An increase in the retarding forces was associated with a rise in RS due to augmentation of load at contact points at a bracket/wire/ligature couple, i.e., increased tipping [6]. This emphasizes the need for a passive levelling arch before applying a mesiodistal traction force, consistent with other studies that simulated retarding forces [45,46,99,102].

3.4. Torque:

When a torque acts, the wire is twisted, leading to an increase of RS [103-105]. Also, RS rises with higher degrees of malocclusion, which is correlative with an increase in angulations in all planes of movement [31,47]. An increase of the inclination in the 3rd order is correlated with an increase in static friction when inclination rises above the critical angle [33,106]. However, the increase in static friction under torque is less than the one caused by tipping [33].

4. Ligation:

4.1. Ligature Materials:

Since ligatures are considered as a cornerstone in orthodontic treatment, the effect of different ligature materials on RS needs to be evaluated. It is widely reported that SS ligatures are associated with lower RS values than conventional elastomeric ligatures (CEL) [12,13,43,107-111]. This can be due to differences in surface properties between SS and elastomers. Also, the metal-to-metal contact offered by SS ligatures leads to smoother sliding due to high polishing of SS. However, SS ligatures may show RS comparable with CEL due to difficulties in standarization of SS ligation [112]. When perturbations (gentle finger strokes on the wire simulating the occlusal displacing forces) were applied to the wire which was ligated by either SS ligatures or CEL, reduction in RS due to perturbations was independent of the change in ligature material [113].

Teflon-coated SS ligatures showed lower static friction than polyurethane elasomeric ligatures since the Teflon coat acts as a solid lubricant [8,13,114]. Similarly, silicon-lubricated elastomeric ligatures caused a lower static friction than the non-lubricated ones [115]. Improvements in surface conditions of ligatures by coatings or lubrications resulted in lower RS values as noticed with slick-coated elastomeric ligatures (SuperSlick®) exhibiting lower static friction than other conventional elastomeric modules, as well as a better abrasion resistance, which influences the initiation of sliding [116]. In agreement with this, some studies reported that slick-coated ligatures showed lower RS value than uncoated ligatures [117,118]. However, SS and Teflon-coated SS ligatures were reported to have superior sliding behavior compared to CEL and SuperSlick® ligatures [13,111].

4.2. Ligation Force (Ligation Technique):

Ligation force differs according to the ligation technique or the type of ligation. Several studies reported a direct relation between ligation force and RS, i.e., the higher the applied ligation force, the higher the RS value [11,24,83,84,119-121].

SLBs are assumed to produce a lower ligation force leading to a lower RS. Small round wires for both active and passive SLBs showed non-significant differences, while with larger rectangular wires the active SLBs showed higher RS than the passive ones. The active SLBs were affected by the increase in the buccolingual dimension of wires leading to higher RS [122]. However, both SLBs show lower RS value than conventionally ligated brackets (CLBs) due to a lower ligation force [9,29,53,83]. As indicated above, other parameters such as bracket material [16,22,55], force decay of elastomeric ligatures [40,92] or bracket dimensions and design [43] may take the upper hand over ligation force, leading to inconsistent results. When tipping is involved, an increased RS value of SLBs is due to the BI component, and irrespective of the ligation force. However, active SLBs also showed higher RS during tipping due to the added higher FR value than passive SLBs (RS = FR + BI) [64,95].

In general, several studies reported that active SLBs showed a higher RS than passive SLBs [33,34,54,66,74,75,77,83,106,116,122]. Moreover, several studies reported that SLBs showed a lower RS than CLBs especially with small round wires [16,18,31,34,35,38,54,57,60,66,74,75,77,81,83,84,97,106,116].

The low RS values obtained when ligating small round wires against SLBs suggest a good option for the alignment phase during orthodontic treatment. In contrast, it was also reported that SLBs showed higher RS than Mini-Twin® CLB [123].

Elastomeric ligatures have various designs and patterns of ligation influencing the ligation force. It was reported that the introduction of a 45° bend into the elastomeric module reduced RS to comparable levels with the SS ligatures [124]. Figure-of-8 ligation method showed higher RS than the conventional ligation [13,109,114]. New designs of elastomeric ligatures, non-conventional elastomers, are considered as passive ligatures as they create less contact with wires. They showed lower ligation force and RS value than conventional designs [89,125,126]. Slide®, low-friction design of elastomeric ligatures, showed lower RS than the conventional one but only with round wires [121]. The size of ligatures was shown not to affect RS significantly [82,121,127]. The Delta Force® CoCr bracket has multiple tie wings to allow different forms of ligation: minimum, medium and maximum ligation [96]. A direct rise in RS was reported at increasing ligation pattern.

5. Oral atmosphere and clinical use:

5.1. Saliva:

For many years a controversy has raged over whether saliva or fluid medium is a lubricant or an adhesive when a bracket is slid through an archwire. Several studies in the literature shed light on the hypothesized lubrication effect of saliva. A reduction of RS at 0° tipping was reported, while at 10°, lubrication was material-dependent [7]. Hence, the lubrication effect of artificial saliva exists when clearance is present between brackets and wires. When clearance disappears, the sliding behavior depends on the chemical and surface properties of tested materials. This was explained by the squeezing out of saliva between bracket and wire when the angulation increases, leading to a direct contact between the studied couple [7,34].

On the other hand, some studies reported an overall increase in RS in the wet state, suggesting an adhesive effect played by saliva against some bracket/wire couples [20,21,95,101,128]. This was explained by the nature of saliva, which is a polar liquid increasing the atomic attraction between ionic species of bracket and wire [128]. Although they had the roughest surface among NiTi and SS wires, βTi wires showed the lowest increase in RS under wet conditions. This was explained by the fact that saliva fills up the irregularities in the βTi wire surface and makes it smoother (lubrication effect) [128]. Similar findings were noticed with respect to SS and βTi wires [129]. The sliding behavior is independent of the degree of saliva viscosity [129].

5.2. Heat and humidity:

Prolonged exposure to an oral medium (saliva, heat, and humidity) may lead to an elastic degradation and an elastic force decay of elastomeric ligatures leading to lower RS value [130]. It may also lead to changes in the structure and surface characteristics of ligatures, affecting RS [131]. However, polyurethane ligature material and slick coated ligatures were reported to be less prone to oral environmental changes than conventional latex [82,132] and uncoated ligatures [116]. Similarly, SS ligatures are least affected by the oral medium [110].

If the oral medium temperature in the case of austenitic NiTi wire increases, RS rises as well [39]. This was explained by an increase in NiTi wire stiffness with higher temperatures leading to a rise in the BI component of RS [39].

5.3. Wear and reconditioning:

Many studies reported that an increase in surface roughness and abrasion of test wires were associated with an oral use leading to an increase in RS [56,60,133-137].

In a similar context, the bracket of highest corrosion resistance (SR-50A) showed decreasing RS with increasing exposure to the oral environment, while brackets with less corrosion resistance (MiniDiamond® and Archist®) showed increasing RS [28]. This was explained by the augmented brackets surface corrosion products, which substantially affect RS. A higher increase in RS was noticed after immersion in artificial saliva at 6.75 pH or in a 0.2% acidified phosphate fluoride solution (APF) reflecting the severity of corrosion caused by APF[138]. On the other hand, when 0.2% chlorhexidine solution was compared with artificial saliva, a non-significant difference between the two solutions was noticed [139]. It was concluded that chlorhexidine-containing mouthwashes can be safely prescribed as a non-destructive prophylactic agent for orthodontic patients. Coatings on orthodontic wires may improve the corrosion resistance and, hence may have a beneficial effect on sliding behavior [70,140].

Wires repeatedly used showed higher RS due to wearing and the abrasion process, leading to a rougher surface[141]. Wear debris generally only has a small influence on static friction, except at a high ligation force, where the static friction markedly increases because of wire bending [24].

A process of reconditioning of used archwires has a non-significant influence on static friction [100]. On the other hand, reconditiong increases RS [142]. On the contrary, it was reported that cleaning and conditioning of clinically used archwires by ultrasound or steel wool sponge resulted in elimination of accumulated debris and improvement of the surface properties, leading to reduction in RS [136]. Air borne polishing caused a rougher, more irregular surface of polished brackets and, hence, increased RS [143,144].

5.4. Occlusal forces:

Few studies focused on the effects of occlusal displacing forces occurring during mastication on RS. However, a general reduction in RS associated with occlusal displacing forces was reported [90,113,145-149]. This was explained as the forces causing the wire to unlock momentarily and to slide. However, that was inconsistent with tests using a loop and a bracket in the buccal sulcus to evaluate RS when patients were masticating a softened chewing gum. It was reported that mastication did not significantly reduce RS [110]. This was possibly due to the position of the test bracket in the buccal sulcus, i.e., not in alignment with the occlusal plane.

5.5. Plaque/Biofilm:

As far as could be determined, none of the studies included in this review investigated whether plaque or pellicle affect RS or not.

5.6. Sliding Velocity:

Only two studies evaluated the influence of the sliding velocity on RS. RS values of SS and NiTi wires were reported to be independent of sliding velocity, while CoCr wire showed a higher RS at lower velocities, and the opposite was noticed on βTi wire [119]. An increase in RS with decreasing sliding velocity was reported [150]. It was stated that Coulomb's law of friction, i.e. "Friction is independent of sliding velocity", was apparently not applicable at extremely low sliding velocities.

5.7. Bracket protectors:

Only one study investigated the difference in RS when two types of bracket protectors were used [151]. The acetate protector showed a non-significant difference with non-protector state; while the temporary resin protector showed a slight increase in RS, possibly due to a larger contact area with the wire.

Conclusion

This systematic review covers a wide range of in vitro studies on RS published in the literature. Within the context of the aim of this review, RS was found to be strongly related to different material and mechanical aspects in different orthodontic treatment options. All reported parameters affecting RS were reviewed. It can be concluded that RS is a multi-factorial event and can affect sliding synergistically. Some parameters were comprehensively evaluated in the literature such as material dimensions, saliva, displacements and transitions. Others still need to be further investigated such as plaque/biofilm and sliding velocity. A good clinical decision should take into account all involved parameters when selecting a bracket/archwire couple to achieve an optimal orthodontic treatment.

Appendix I: Quality assessment methodological score of selected studies.

Author	Clearly stated aim?	Selection criteria described?	Similar baseline characteristics?	Sample size reported?	Sample size ≥ 5?	Co-intervention?	Blinding?	Repetition of test ≥ 3?	Intra-observer reproducibility?	Inter-observer reproducibility?	Conflict of interest avoided?	Adequate statistical analysis?	Score
Nicolls 1968[152]	/	×	×	×	×	×	×	×	×	×	✓	×	1.5
Liew 2002[146]	✓	×	✓	×	×	×	×	×	×	×	✓	×	3
Redlich 2008[153]	✓	✓	×	×	×	✓	×	×	×	×	×	×	3
Schumacher1999[154]	✓	×	×	×	×	×	×	×	×	×	✓	✓	3
Articolo 1999[91]	✓	×	×	×	×	/	×	×	×	×	✓	✓	3.5
Husain 2011[155]	✓	✓	×	×	×	/	×	×	×	×	✓	×	3.5
Katz 2006[156]	✓	✓	✓	×	×	/	×	×	×	×	×	×	3.5
Kuroe 1994[157]	✓	✓	×	×	×	/	×	✓	×	×	×	×	3.5
Rapiejko 2009[158]	✓	×	/	×	×	✓	×	×	×	×	✓	×	3.5
Kusy 2000[49]	✓	✓	×	×	×	×	×	×	×	×	✓	✓	4
Stannard 1986[159]	✓	×	×	×	×	×	×	✓	×	×	✓	✓	4
Downing 1995[128]	✓	×	/	×	×	×	×	✓	×	×	✓	✓	4.5
Drescher 1989[6]	✓	×	×	✓	×	/	×	✓	×	×	✓	×	4.5
Edwards 1995[114]	✓	/	×	×	×	×	×	✓	×	×	✓	✓	4.5
Jordan 2012[160]	✓	✓	/	×	×	✓	×	×	×	×	✓	×	4.5
Khalid 2012[161]	✓	✓	/	×	×	×	×	×	×	×	✓	✓	4.5
Kusy 1990[47]	✓	×	×	✓	×	/	×	×	×	×	✓	✓	4.5
Kusy 2001[162]	✓	✓	/	×	×	×	×	×	×	×	✓	✓	4.5
Park 2004[163]	✓	×	/	×	×	×	×	✓	×	×	✓	✓	4.5
Pizzoni 1998[164]	✓	✓	×	/	×	×	×	×	×	×	✓	✓	4.5
Thorstenson2003[165]	✓	×	/	×	×	×	×	✓	×	×	✓	✓	4.5
Tidy 1989[45]	✓	×	×	✓	×	×	×	✓	×	×	✓	✓	4.5
Wilmes	✓	×	/	×	×	✓	×	×	×	×	✓	✓	4.5

2009[143]												
Andreasen 1970[4]	✓	/	/	✓	×	×	×	✓	×	×	✓	×	5
Crincoli 2013[36]	✓	✓	×	×	×	×	×	✓	×	×	✓	✓	5
Gil 1998[166]	✓	✓	✓	×	×	✓	×	×	×	×	✓	×	5
Hamdan 2008[167]	✓	×	✓	×	×	×	×	✓	×	×	✓	✓	5
Huang 2013[168]	✓	✓	✓	×	×	✓	×	×	×	×	✓	×	5
Ireland 1991[169]	✓	✓	/	×	×	/	×	×	×	×	✓	✓	5
Kusy 1991[48]	/	×	/	✓	×	✓	×	×	×	×	✓	✓	5
Murayama2013[85]	✓	✓	×	×	×	✓	×	×	×	×	✓	✓	5
Peterson 1982[170]	✓	✓	×	✓	×	×	×	✓	×	×	✓	×	5
Schumacher1998[171]	✓	/	/	×	×	✓	×	✓	×	×	✓	×	5
Suwa 2003[172]	✓	✓	/	×	×	/	×	✓	×	×	×	✓	5
Taylor 1996[173]	/	×	/	✓	×	✓	×	✓	×	×	✓	×	5
Thiry 2010[174]	✓	✓	/	×	×	✓	×	/	×	×	✓	×	5
Thorstenson2003[175]	✓	✓	/	×	×	/	×	×	×	×	✓	✓	5
Whitley 2007[176]	✓	✓	✓	×	×	×	×	×	×	×	✓	✓	5
Whitley 2007[51]	✓	×	/	×	×	✓	×	×	/	×	✓	✓	5
Yamaguchi 1996[99]	✓	×	✓	×	×	×	×	✓	×	×	✓	✓	5
Berger 1990[177]	✓	✓	/	✓	×	×	×	✓	×	×	✓	×	5.5
Chung 2009[105]	✓	×	/	✓	✓	×	×	×	×	×	✓	✓	5.5
Fidalgo 2011[178]	✓	×	/	×	×	✓	×	✓	×	×	✓	✓	5.5
Fourie 2009[88]	✓	×	×	/	✓	×	×	✓	×	×	✓	✓	5.5
Gandini 2008[179]	✓	✓	×	/	×	×	×	✓	×	×	✓	✓	5.5
Heo 2011[87]	✓	✓	/	×	×	×	×	✓	×	×	✓	✓	5.5
Hsu 2009[180]	✓	✓	/	×	×	×	×	✓	×	×	✓	✓	5.5
Husmann 2002[73]	✓	/	/	/	×	×	×	✓	×	×	✓	✓	5.5
Khambay2005[181]	✓	/	✓	×	×	✓	×	×	×	×	✓	✓	5.5

✓ **Good (1); / : Average (0.5); × : Poor (0)**

Appendix I: Quality assessment methodological score of selected studies (cont.)

Author	Clearly stated aim?	Selection criteria described?	Similar baseline characteristics?	Sample size reported?	Sample size ≥ 5?	Co-intervention?	Blinding?	Repetition of test ≥ 3?	Intra-observer reproducibility?	Inter-observer reproducibility?	Conflict of interest avoided?	Adequate statistical analysis?	Score
Kusy 1989[119]	✓	✓	×	✓	×	/	×	/	×	×	✓	×	5.5
Kusy 1993[71]	✓	✓	/	×	×	✓	×	×	×	×	✓	✓	5.5
Kusy 1995[129]	✓	✓	/	×	×	×	×	✓	×	×	✓	✓	5.5
Kusy 2004[3]	✓	✓	/	×	×	✓	×	×	×	×	✓	✓	5.5
Leander 2011[118]	✓	✓	/	×	×	×	×	✓	×	×	✓	✓	5.5
Meier 2014[182]	✓	✓	/	×	×	✓	×	×	×	×	✓	✓	5.5
Moore 2004[104]	✓	/	✓	×	×	×	×	✓	×	×	✓	✓	5.5
Reicheneder2008[183]	✓	✓	×	/	✓	×	×	×	×	×	✓	✓	5.5
Rucker 2002[184]	✓	/	×	✓	×	✓	×	×	×	×	✓	✓	5.5
S.Naveh 2009[185]	✓	✓	/	×	×	✓	×	✓	×	×	×	✓	5.5
Saunders 1993[186]	✓	✓	/	×	×	✓	×	×	×	×	✓	✓	5.5
Shivapuja1994 [187]	✓	/	×	✓	✓	×	×	×	×	×	✓	✓	5.5
Vinay 2014[188]	✓	/	×	✓	✓	×	×	×	×	×	✓	✓	5.5
Wei 2011[189]	✓	✓	/	×	×	✓	×	✓	×	×	✓	×	5.5
Braun 1999[113]	✓	✓	✓	×	×	✓	×	✓	×	×	✓	×	6
Chang 2013[39]	✓	✓	/	×	×	/	×	✓	×	×	✓	✓	6
Clocheret2004 [190]	✓	✓	/	×	×	×	×	✓	×	/	✓	✓	6
Frank 1980[44]	✓	×	×	✓	✓	×	×	✓	×	×	✓	✓	6
Hain 2003[109]	✓	✓	✓	×	×	×	×	×	×	✓	✓	✓	6
Hiroce 2012[191]	✓	✓	×	✓	✓	×	×	×	×	×	✓	✓	6
Kusy 1990[192]	✓	✓	×	✓	×	✓	×	×	×	×	✓	✓	6
Kusy 1992[193]	✓	✓	×	✓	×	✓	×	×	×	×	✓	✓	6
Kusy 1998[78]	✓	✓	✓	×	×	✓	×	×	×	×	✓	✓	6
Mendonca	✓	×	/	/	✓	×	×	✓	×	×	✓	✓	6

2014[151]													
Muguruma 2011[194]	✓	✓	×	✓	✓	×	×	×	×	×	✓	✓	6
Redlich 2003[195]	✓	×	×	✓	✓	×	×	✓	×	×	✓	✓	6
Redlich 2008[196]	✓	✓	✓	/	×	/	×	✓	×	×	×	✓	6
Regis 2011[197]	✓	×	/	✓	✓	/	×	×	×	×	✓	✓	6
Suryaw. 2013[198]	✓	✓	×	✓	×	×	×	✓	×	×	✓	✓	6
Tecco 2009[121]	✓	×	×	✓	✓	×	×	✓	×	×	✓	✓	6
Thorstenson2004[37]	✓	✓	/	✓	×	/	×	×	×	×	✓	✓	6
Yanase 2014[150]	✓	×	/	/	✓	×	×	✓	×	×	✓	✓	6
Bednar 1991[107]	✓	/	×	✓	/	/	×	✓	×	×	✓	✓	6.5
Berradja 2006[199]	✓	✓	/	✓	×	×	×	✓	×	×	✓	✓	6.5
Budd 2008[29]	✓	✓	/	✓	×	×	×	✓	×	×	✓	✓	6.5
Chimenti 2005[115]	✓	/	✓	✓	×	×	×	✓	×	×	✓	✓	6.5
Choi 2014[200]	✓	/	×	✓	✓	✓	×	×	×	×	✓	✓	6.5
Cunha 2011[130]	✓	✓	/	✓	✓	×	×	×	×	×	✓	✓	6.5
Farronato2012 [201]	✓	×	/	✓	✓	×	×	✓	×	×	✓	✓	6.5
Jones 2007[202]	✓	✓	/	✓	✓	×	×	×	×	×	✓	✓	6.5
Kahlon 2010[203]	✓	×	/	✓	✓	×	×	✓	×	×	✓	✓	6.5
Kao 2006[138]	✓	×	×	✓	✓	/	×	✓	×	×	✓	✓	6.5
Kapila 1990[42]	✓	/	×	✓	✓	×	×	✓	×	×	✓	✓	6.5
Kapur 1998[204]	✓	✓	×	✓	✓	/	×	×	×	×	✓	✓	6.5
Keith 1994[205]	✓	✓	/	✓	×	✓	×	×	×	×	✓	✓	6.5
Khambay2004 [124]	✓	✓	/	×	×	✓	×	✓	×	×	✓	✓	6.5
Kim 2008[74]	✓	✓	/	×	×	×	×	✓	✓	×	✓	✓	6.5
Leal 2014[206]	✓	×	/	✓	✓	×	×	✓	×	×	✓	✓	6.5
Loftus 2001[94]	✓	×	✓	✓	×	×	×	✓	/	×	✓	✓	6.5
Muguruma 2014[106]	✓	✓	/	✓	✓	×	×	×	×	×	✓	✓	6.5

✓: Good (1); / : Average (0.5); × : Poor (0)

Appendix I: Quality assessment methodological score of selected studies (cont.)

Author	Clearly stated aim?	Selection criteria described?	Similar baseline characteristics?	Sample size reported ?	Sample size ≥ 5?	Co-intervention?	Blinding ?	Repetition of test ≥ 3?	Intra-observer reproducibility?	Inter-observer reproducibility?	Conflict of interest avoided?	Adequate statistical analysis?	Score
Pratten 1990[207]	✓	✓	×	✓	×	/	×	✓	×	×	✓	✓	6.5
Prososki 1991[208]	✓	✓	/	✓	×	✓	×	×	×	×	✓	✓	6.5
Rajakulendran 2006[209]	✓	✓	/	✓	✓	×	×	×	×	×	✓	✓	6.5
Reimann 2012[142]	✓	×	/	✓	✓	✓	×	×	×	×	✓	✓	6.5
Saunders 1994[67]	✓	✓	/	✓	×	✓	×	×	×	×	✓	✓	6.5
Sims 1994[103]	✓	×	/	✓	✓	×	×	✓	×	×	✓	✓	6.5
Stefanos 2010[210]	✓	✓	×	/	✓	×	×	✓	×	×	✓	✓	6.5
Tanne 1994[98]	✓	✓	×	✓	×	/	×	✓	×	×	✓	✓	6.5
Thorstenson2001[211]	✓	✓	/	✓	✓	×	×	×	×	×	✓	✓	6.5
Varela 2014[212]	✓	✓	/	✓	✓	✓	×	×	×	×	✓	×	6.5
Vaughan 1995[19]	/	✓	×	✓	✓	×	×	✓	×	×	✓	✓	6.5
Wong 2014[213]	✓	✓	/	✓	✓	×	×	×	×	×	✓	✓	6.5
Yanase 2009[214]	✓	✓	×	/	✓	×	×	✓	×	×	✓	✓	6.5
Zufall 1998[68]	✓	✓	/	/	×	/	×	✓	×	×	✓	✓	6.5
Alavi 2011[215]	✓	✓	/	✓	✓	/	×	×	×	×	✓	✓	7
Al-Khatib2005[216]	✓	✓	✓	×	×	✓	×	✓	×	×	✓	✓	7
Bazakidou 1997[217]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Brauchli 2011[75]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Cacciafesta2003[55]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Castro 2013[38]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Chng 2014[218]	✓	✓	×	✓	×	✓	×	✓	×	×	✓	✓	7

Dickson 1994[63]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Dowling 1998[219]	✓	✓	✓	✓	✓	×	×	×	×	×	✓	✓	7
Fernandes 2010[18]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7
Grosgogeat 2006[72]	✓	×	×	✓	✓	✓	×	✓	×	×	✓	✓	7
Guerrero 2010[220]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Henao 2004[34]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Ho 1991[221]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Ioi 2009[127]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Jakob 2014[222]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Kapur 1999[141]	✓	×	/	✓	✓	/	×	✓	×	×	✓	✓	7
Kumar 2014[223]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Kusy 2000[93]	✓	✓	✓	✓	×	×	×	×	×	✓	✓	✓	7
Liu 2013[135]	✓	×	×	✓	✓	✓	×	✓	×	×	✓	✓	7
Matarese 2008[224]	✓	×	✓	✓	✓	×	×	✓	×	×	✓	✓	7
Mendes 2014[225]	✓	/	/	✓	✓	✓	×	×	×	×	✓	✓	7
Nucera 2013[41]	✓	✓	×	/	✓	/	×	✓	×	×	✓	✓	7
Ogata 1996[79]	✓	×	✓	✓	✓	×	×	✓	×	×	✓	✓	7
Omana 1992[46]	✓	✓	/	✓	×	/	×	✓	×	×	✓	✓	7
Parmagnani 2012[144]	✓	✓	/	✓	✓	/	×	×	×	×	✓	✓	7
Pliska 2014[22]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
ReadWard1997[80]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Ribeiro 2012[134]	✓	×	✓	✓	✓	✓	×	×	×	×	✓	✓	7
Rongo 2014[137]	✓	/	/	✓	×	✓	×	✓	×	×	✓	✓	7
Rozzi 2010[226]	✓	✓	/	/	✓	×	×	✓	×	×	✓	✓	7
Rudge 2015[227]	✓	/	/	✓	✓	✓	×	×	×	×	✓	✓	7
Santos	✓	×	✓	✓	✓	✓	×	×	×	×	✓	✓	7
Sirisaow. 2006[147]	✓	✓	/	/	✓	×	×	✓	×	×	✓	✓	7
Tecco 2005[120]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7

✓: **Good (1); / : Average (0.5); × : Poor (0)**

Appendix I: Quality assessment methodological score of selected studies (cont.)

Author	Clearly stated aim?	Selection criteria described?	Similar baseline characteristics?	Sample size reported?	Sample size ≥ 5?	Co-intervention?	Blinding?	Repetition of test ≥ 3?	Intra-observer reproducibility?	Inter-observer reproducibility?	Conflict of interest avoided?	Adequate statistical analysis?	Score
Sukh 2013[12]	✓	✓	/	/	✓	×	×	✓	×	×	✓	✓	7
Tecco 2007[83]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Tecco 2011[31]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Tecco 2011[84]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Thomas 1998[53]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Tselepis 1994[7]	✓	/	/	✓	✓	×	×	✓	×	×	✓	✓	7
Wadhwa 2004[17]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Williams 2013[16]	✓	✓	×	✓	✓	×	×	✓	×	×	✓	✓	7
Zufall 2000[229]	✓	✓	/	✓	✓	/	×	×	×	×	✓	✓	7
Alfonso 2013[69]	✓	✓	/	✓	✓	✓	×	×	×	×	✓	✓	7.5
Angolkar 1990[10]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Araujo 2014[230]	✓	✓	/	✓	✓	✓	×	×	×	×	✓	✓	7.5
Arun 2011[117]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Baccetti 2006[89]	✓	/	✓	✓	✓	×	×	✓	×	×	✓	✓	7.5
Baker 1987[231]	✓	/	✓	✓	✓	×	×	×	✓	×	✓	✓	7.5
Cacciafesta2003[232]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Cash 2004[59]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Cordasco 2012[97]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Crawford 2010[233]	✓	/	✓	✓	✓	✓	×	×	×	×	✓	✓	7.5
DeFranco1995 [8]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Espinar 2011[234]	✓	✓	/	✓	✓	✓	×	×	×	×	✓	✓	7.5
Franchi 2008[125]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Galvão	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5

2013[126]													
Griffiths 2005[235]	✓	/	/	✓	✓	×	×	✓	/	×	✓	✓	7.5
Henao 2004[66]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Jones 2009[82]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Kachoei 2013[236]	✓	×	✓	✓	✓	/	×	✓	×	×	✓	✓	7.5
Kapur 1999[237]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Kim 2014[238]	✓	✓	×	✓	✓	/	×	✓	×	×	✓	✓	7.5
Krishnan 2004[102]	✓	✓	/	✓	✓	✓	×	×	×	×	✓	✓	7.5
Krishnan 2009[54]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Kumar 2014[239]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Leite 2014[240]	✓	✓	×	✓	✓	/	×	✓	×	×	✓	✓	7.5
Lombardo 2013[43]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Mendes 2003[40]	✓	✓	×	✓	✓	/	×	✓	×	×	✓	✓	7.5
Monteiro 2014[241]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Muguruma 2013[242]	✓	✓	/	✓	✓	✓	×	×	×	×	✓	✓	7.5
Nair 2012[25]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Nik 2013[139]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
O'Reilly 1999[145]	✓	×	/	✓	✓	✓	×	✓	×	×	✓	✓	7.5
Oh 2005[28]	✓	✓	/	✓	✓	✓	×	✓	×	×	×	✓	7.5
Ortan 2012[243]	✓	✓	×	✓	✓	/	×	✓	×	×	✓	✓	7.5
Pacheco 2011[244]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Pillai 2014[245]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Pliska 2011[92]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Reicheneder 2007[60]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Sims 1993[77]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Tecco 2010[11]	✓	✓	×	✓	✓	/	×	✓	×	×	✓	✓	7.5
Thorstenson2002[64]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Thorstenson2002[95]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5

✓ Good (1); / : Average (0.5); × : Poor (0)

Appendix I: Quality assessment methodological score of selected studies (cont.)

Author	Clearly stated aim?	Selection criteria described?	Similar baseline characteristics?	Sample size reported?	Sample size ≥ 5?	Co-intervention?	Blinding?	Repetition of test ≥ 3?	Intra-observer reproducibility?	Inter-observer reproducibility?	Conflict of interest avoided?	Adequate statistical analysis?	Score
Lalithapriya 2015[101]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Pattan 2014[13]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
Vijayalakshmi 2009[246]	✓	✓	/	✓	✓	✓	×	×	×	×	✓	✓	7.5
Voudouris2010[57]	✓	✓	/	✓	✓	×	×	✓	×	×	✓	✓	7.5
AlMansouri 2011[132]	✓	×	✓	✓	✓	✓	×	✓	×	×	✓	✓	8
Arici 2015[26]	✓	✓	/	✓	✓	/	×	✓	×	×	✓	✓	8
Bandeira 2011[62]	✓	✓	/	✓	✓	/	×	✓	×	×	✓	✓	8
Bortoly 2008[111]	✓	✓	×	/	✓	✓	×	✓	×	×	✓	✓	8
Bravo 2014[70]	✓	✓	✓	✓	✓	✓	×	×	×	×	✓	✓	8
Cordasco 2009[112]	✓	✓	✓	✓	✓	×	×	✓	×	×	✓	✓	8
Downing 1994[23]	✓	✓	/	✓	✓	/	×	✓	×	×	✓	✓	8
Huang 2012[32]	✓	✓	/	✓	✓	/	×	✓	×	×	✓	✓	8
Inami 2015[247]	✓	✓	×	✓	✓	✓	×	✓	×	×	✓	✓	8
Kao 2011[140]	✓	/	/	✓	✓	✓	×	✓	×	×	✓	✓	8
Keith 1993[24]	✓	✓	/	✓	✓	/	×	✓	×	×	✓	✓	8
Krishnan 2012[58]	✓	✓	✓	✓	✓	✓	×	×	×	×	✓	✓	8
Lee 2001[248]	✓	/	/	✓	✓	✓	×	✓	×	×	✓	✓	8
Lee 2015[81]	✓	✓	/	✓	✓	/	×	✓	×	×	✓	✓	8
Oliver 2011[122]	✓	✓	/	/	✓	×	×	✓	✓	×	✓	✓	8
Oz 2012[123]	✓	✓	×	✓	✓	✓	×	✓	×	×	✓	✓	8
Pimentel 2013[21]	✓	✓	✓	✓	✓	×	×	✓	×	×	✓	✓	8
Reznikov 2010[86]	✓	✓	×	✓	✓	✓	×	✓	×	×	✓	✓	8
Voudouris1997[108]	✓	✓	/	✓	✓	✓	×	✓	×	×	✓	/	8
Willems 2001[50]	✓	✓	✓	✓	✓	×	×	✓	×	×	✓	✓	8

Yeh 2007[33]	✓	✓	×	✓	✓	✓	×	✓	×	×	✓	✓	8
Cha 2007[14]	✓	✓	✓	✓	✓	/	×	✓	×	×	✓	✓	8.5
Doshi 2011[15]	✓	✓	/	✓	✓	✓	×	✓	×	×	✓	✓	8.5
Edwards 2012[131]	✓	✓	/	✓	✓	✓	×	×	✓	×	✓	✓	8.5
Hain 2006[116]	✓	✓	×	✓	✓	/	×	✓	✓	×	✓	✓	8.5
Juvvadi 2010[61]	✓	✓	/	✓	✓	✓	×	✓	×	×	✓	✓	8.5
Liu 2013[35]	✓	✓	/	✓	✓	✓	×	✓	×	×	✓	✓	8.5
Loftus 1999[9]	✓	✓	/	✓	×	✓	×	✓	✓	×	✓	✓	8.5
Michelberger2 000[27]	✓	✓	×	✓	✓	/	×	✓	✓	×	✓	✓	8.5
Nishio 2004[30]	✓	✓	✓	✓	✓	/	×	✓	×	×	✓	✓	8.5
Tai 2015[76]	✓	✓	×	✓	✓	✓	×	✓	×	×	✓	✓	8.5
Wichelhaus 2005[56]	✓	✓	/	✓	✓	✓	×	✓	×	×	✓	✓	8.5
Garner 1986[52]	✓	✓	/	✓	✓	/	×	✓	✓	×	✓	✓	9
Haskova 2008[96]	✓	✓	✓	✓	✓	×	×	✓	✓	×	✓	✓	9
Iwasaki 2003[110]	✓	×	✓	✓	✓	✓	×	✓	✓	×	✓	✓	9
Jones 2002[100]	✓	✓	✓	✓	✓	✓	×	✓	×	×	✓	✓	9
Liaw 2007[65]	✓	✓	✓	✓	✓	✓	×	✓	×	×	✓	✓	9
Marques 2010[133]	✓	✓	✓	✓	✓	✓	×	✓	×	×	✓	✓	9
Normando 2013[136]	✓	✓	✓	✓	✓	✓	×	✓	×	×	✓	✓	9
Olson 2012[148]	✓	×	×	✓	✓	✓	×	✓	✓	✓	✓	✓	9
Sadique 2006[20]	✓	✓	×	✓	✓	✓	×	✓	✓	×	✓	✓	9
Seo 2014[149]	✓	✓	✓	✓	✓	✓	×	✓	×	×	✓	✓	9
Seo 2014[90]	✓	✓	✓	✓	✓	✓	×	✓	×	×	✓	✓	9

✓: Good (1); / : Average (0.5); × : Poor (0)

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